TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 618

RELATIVE ECONOMY OF DIFFERENT METHODS OF AIRPLANE CONSTRUCTION

By H. Herrmann

Zeitschrift für Flugtechnik und Motorluftschiffahrt
November 14 and 28, 1930
Verlag von R. Oldenbourg, München und Berlin

Washington
April, 1931

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By H. Herrmann

A comparison of the relative economy of different kinds of airplane construction shows that monoplanes are cheaper than biplanes; that all-metal construction is much more expensive than mixed construction; that multi-engine airplanes are more expensive than single-engine types of the same carrying capacity and speed; that the cost of airplanes is materially reduced by increasing their size without increasing the number of engines; that the greatest economy usually coincides with the best aerodynamic and static conditions; and that the cost is always increased by safety requirements.

The lack of data on the economic aspects of different methods of airplane construction is a great difficulty. Aerodynamic and static researches, on the other hand, are supplied with accurate data by wind-tunnel and strength tests, the results of which are found in the technical press. During his many years of activity as an airplane designer many analyses of his own and of other designers' constructions have come under his notice. The first attempt to utilize these analyses was made about two and a half years ago. It proved a complete failure, owing to

*"Ueber die Wirtschaftlichkeit in der Fertigung der verschiedenen Bauverfahren von Flugzeugen." From Zeitschrift für Flugtechnik und Motorluftschiffahrt, November 14 and 28, 1930. This report is based on the state of aeronautical development of the summer of 1929.

the practical impossibility of drawing general conclusions from the comparison of two different makes. The main items are labor, general expenses, and materials. These three factors are intimately related but are not of much use, because they vary so greatly in different factories and even in the same factory within a short time, according to the quantity of production. A year later useful results were obtained by an investigation of the manufacture of airplane wings. This method was then successfully applied to other parts and finally enabled us to make instructive comparisons between several quite different airplane types.

Our task would be greatly facilitated by tables containing the figures of the different estimates, but no German or foreign aircraft manufacturer would release such data. It is therefore very difficult to obtain any useful information, since the publication of estimates usually causes financial harm to the company. Moreover, the working conditions of a factory are always affected by the quantity of production, the trend of business, the experience of the workmen, the equipment and many other factors.

The cost of materials will be investigated first, then the various structural components and their influence on the finished part, from which conclusions will be drawn regarding the whole airplane. The effect of size on the methods of construction to be employed will be investigated in a similar manner.

This investigation is confined to airplanes filling the specifications of the different air ministries and therefore accepted on public service lines. If these regulations, drawn up for public safety, were disregarded, airplanes might be built cheaper, but would not sell. Unusual airplane types of more than 20 to 25 tons are beyond the scope of this investigation.

M a t e r i a l s*

Waste and purchasing expenses, for which we have empirical figures, must be added to the cost of materials used in airplane construction. Wood for spar construction must first be cut into strips and glued. The waste varies for different species of wood, being less for spruce than for pine. The fine-grained strong Polish pine, which grows on sandy ground, yields less waste than German pine. But even with Polish pine the waste is so great that pine spars and ribs became very rare in Germany after the war. During the war all spars were made of pine without requiring much additional weight. Sheet-metal and plywood plates yield waste, for which we have empirical figures. Thick sheet-metal fittings with many lightening holes yield much waste. Their thickness and the number of lightening holes can often be reduced by structural changes without affecting the weight and strength. Sheet-metal plates of the same size are used in both cases, yet in one case they are thick and considerably lightened

*Figures 1-4 were plotted eighteen months ago. Plywood prices are now much higher, while those of metal are expected to drop.

while in the other they are thin and only slightly lightened. Thin plates are cheaper and require less work.

Economy of material means lower cost of production. The considerable waste in the case of wood and sheet metal is obviously at the expense of the airplane manufacturer, as it increases the cost of labor, the space requirements, the machine-tool equipment and the transportation requirements. The cost of the material, however, not only includes the waste, but also the purchasing and delivery expenses. The purchasing cost is much greater in aircraft construction than in other branches of industry, owing to the very exacting material tests. Like shipbuilding, aircraft construction has to rely on many subsidiary manufacturers.

Sheet metal and fabric are subjected to tensile tests. Rods are ball-tested and tubes and wood undergo compression tests. Of course, rods, wood, and tubes occasionally undergo tensile tests, but materials bought in large quantities must be checked in a cheap and simple manner. Large deliveries of plywood are light-tested with powerful lamps. Only samples are machine tested. In the case of wood, a sample from each plank is tested by compression. Wood, which yields little waste, can be tested at smaller cost, since less raw material is then required for an equal number of finished parts. The cost of nearly all materials is affected by several factors.

Sheet metal and plywood can be compared only per unit of area, the coefficients of strength and elasticity and the methods of assembly being taken into consideration. Sheet brass is the most expensive and can be obtained only in small plates. It is used in tank construction and assembled by soldering and riveting. Duralumin, which is cheaper than brass, can be obtained in very large plates or sheets of 1 mm (0.04 in.) or more in thickness. It can only be riveted, while elektron can be welded. Owing to its low specific gravity, its thickness can be easily increased, thus affording sufficient local strength for cowlings, etc. Aluminum also has good welding properties and is available in very large sheets. Sheet steel is the cheapest of all sheet metal and its price is beaten only by plywood. The cost of very thin plywood and elektron per unit weight is very high, due to the cost of production which increases with decreasing thickness of the sheets.

According to Figure 3, all thin-walled tubes of small diameter are quite expensive. Statically equivalent open sections are 20% heavier but nearly 50% cheaper. Small open sections are therefore given preference, when the cost of the special tool equipment for their assembly is warranted by the large number of pieces, especially for wing ribs. Large open sections in duralumin construction offer the double advantage of low cost and convenient riveting.

Structural Parts

a) Wing structure, fittings, spars, ribs, struts, etc. Cantilever wings versus braced biplane wings.- From the fittings, struts, bracings, spars, ribs, etc., the investigation of the cost of production is extended to the whole wing. In the course of years many forms have been evolved for the same fittings. A certain standardization has gradually developed. The use of especially high-grade materials is of no advantage, since the necessity of maintaining low crushing and superficial pressures seldom permit any saving in weight. In each case a certain cross section for the absorption of the forces must be provided at the lowest possible cost. There is more waste in making turned and milled fittings than in composite sheet-metal fittings. Besides, it is not always possible to make complicated fittings from a single piece. Welding of sheet-metal parts is the only possible means of economically producing closed hollow bodies with their great structural advantages. As a rule, fittings properly assembled from welded sheet-metal parts are the cheapest and lightest. The use of weldable chrome-molybdenum sheet steel with its great seam strength of 65 kg/mm^2 (92,450 lb./sq.ft.) is particularly desirable in this case.

Riveted duralumin fittings are seldom lighter. Weldable sheet steel is about as strong as refined light metals, but three times as heavy. The edges of welded sheets are fused together by welding wire, while the edges of riveted sheets overlap one another. Inasmuch as the crushing pressure on the face of the rivet holes must be kept within certain limits, the weight of riveted joints is often increased to such an extent by the overlapping that the use of welded steel saves weight, especially for closed parts.

Nearly all airplanes have more or less similar wing ribs. In tapered wings, only two ribs are always unchanged. In Germany wooden ribs usually consist of plywood webs with glued and nailed flanges. Twelve to eighteen ribs are simultaneously cut from plywood and quickly assembled, the flanges being put in jigs and the webs glued under pressure. After 12 hours the ribs are finished and, if necessary, lightly nailed. Several jigs are required for letting the glue dry. Hence it is only a small step from the number of jigs required for the cutting of plywood webs and the gluing of ribs with uniform chord to the greater number of jigs for tapered wings. These conditions differ from those of duralumin ribs, which are assembled, drilled and riveted in one and the same jig. A great number of ribs can be made in a very short time with a single machine, which, however, is usually very expensive. Tapered metal wings are therefore less common than wooden ones. Thin-walled welded tubular steel ribs have been successfully used in an airplane type of which only a few were built. Duralumin ribs are used in large English and American flying boats and are very expensive. Even with good machines the cost of labor for all rib types is very high. It can be reduced only by further increasing the cost of the tool equipment. A factory in the United States now specializes in the production of ribs for different aircraft factories. Steel U sections are used, the hard-soldered joints being made on special machines. Cheap material is thus machined with a minimum cost of labor. The absence of straps and rivets, with the weakening holes, partly compensates for the greater weight of steel as compared with light metals. This compensation can also be achieved by greater strength of material. This method deserves serious consideration, despite the difficulty of protecting thin-walled ribs from corrosion. Even a very little rust greatly reduces the strength of thin walls. Thin, stamped steel or duralumin ribs are usually heavier than tubular or U section ribs, owing to the less favorable cross sections. Stamped ribs, especially with short chords, can be produced in large numbers more cheaply than U section or tubular ribs of the same material.

The spacing of the ribs, which varies, in practice, between 20 and 40 cm (7.87 and 15.75 in.) is of considerable importance. One strong rib is not only much cheaper, but also lighter than two weak ribs. Narrower spacing should be used on heavily loaded wings for high speeds. The cost of fabric covering, sewed to a greater number of ribs, is thereby increased. It is approximately 20% of the cost of a wooden wing. The cost of the fabric covering of a wing with many fittings, inspection flaps, end ribs, tank openings, etc., increases approximately in proportion to the cost of the wing. It has been found more expensive to fit fabric on open metal sections than on wooden ribs, sharp edges which chafe the seams having to be avoided. This difficulty is overcome by using tubular ribs.

A distinction must be made between the spars of cantilever wings and those of externally braced wings. The flange thickness of cantilever wings must be greatly increased toward the root on account of the great bending moment. Other wings may have flanges of uniform section running to the outer joint without excessively increasing the weight. Similar considerations apply to the web, which works in shear. The cross sections in Figure 5 are now used in wood construction. Flanges have rectangular sections and are not lightened. Even for the rear spar, usually of less height, cross sections other than rectangular are avoided. It is often a mistake to try to save weight by using spars of the type of Figure 5. Two extensively used types of metal spars are shown in Figure 6.

Many kinds of struts were formerly made. Struts are compression members, for which the modulus of elasticity of the material is even more important than the compressive strength. This has gradually led to a standardization, in which high-grade chrome-nickel-steel struts are being supplanted by standard weldable-steel struts. Wooden struts seem to be definitely eliminated. Duralumin struts are used occasionally. Chrome-nickel-steel struts are now used only in the circular form. They are usually faired to reduce drag and provided with heads cut from the solid. Tubes, heads and fairings are quite expensive. In many cases thin-walled tubes are easily dented. The difficulty of fitting the head in a water-tight manner offers the danger of internal corrosion of the thin wall. Chrome-nickel-steel struts are therefore seldom used. Carbon-steel tubes are either circular and faired or drawn streamlined without fairing. Faired circular tubes are nearly as heavy as streamlined tubes without fairing. The latter have, however, a smaller drag for practically the same strength and weight. It is also easier and cheaper to weld a water-tight head on streamlined struts than on circular ones. Streamlined struts are cheaper, owing to the absence of fairings and to the simpler head.

Struts usually have a fixed welded head with fork or eye joint on one end and a threaded socket on the other, carrying adjustable forks, eye or ball joints which are the most expensive kind. Forks with universal joints can easily be made interchangeable by means of gauges. Ball-turning lathes are provided for balls and ball seats, but they do not insure absolute roundness. It is particularly difficult and expensive to check the spherical part, especially since no standardized tools and gauges are available, as for bolts and bores.

The continuous wing of a cantilever high-wing monoplane is usually secured to the fuselage by four fittings. The spars require no connections for struts and bracings, no wing-root ribs, but only aileron hinges and bent outer edges. Wings made in several sections are more expensive. The cost is considerably increased by external bracing, which requires wing fittings and stiffening of the bottom fuselage flanges and fittings. A comparison of the different types of construction shows that struts enable but little weight reduction on commercial airplanes. They do enable, however, a valuable uniformity in the length of ribs and spar flanges, especially of fabric-covered metal wings, since uniform cantilever wings cannot be used, owing to the excessive weight of the spars.

Struts are justified on military airplanes by several considerations. Twin struts are often used to insure great structural strength, stiffness and complete absence of vibration, especially of thin wings. They guarantee full flying ability to airplanes after the failure of any one of their structural parts. Besides, more money is available for military airplanes than for commercial machines.

Cantilever biplanes with continuous lower wing require four spars instead of two, for the same total wing area, the length of these spars considerably exceeding that of the two thick spars of a monoplane. This increases the cost of labor since, regardless of the flange thickness, the spars must be machined, glued and nailed throughout their whole length, as likewise the fittings and blocks for the necessary outboard strut. Metal spars must be drawn or rolled in exactly the same manner, but over a greater length, and then riveted and provided with fittings. Four bent biplane edges are more expensive than the two edges of the corresponding monoplane. The same is true of the four ailerons with their hinges and controls.

The weight, but not the length, of the spar flanges is reduced by bracing. The machined length is unchanged. The difficulty and cost of producing long thin flanges outweighs the saving in material. A wing-root rib with its stiffenings costs four to six times as much as an ordinary rib. Additional bracings require more material and labor in addition to the cost of assembling. The fittings and end ribs of divided lower wings are more expensive than the eliminated wing portion below the fuselage. Moreover, monoplanes have a smaller number of ribs. The assembling of the wing is also cheaper since, aside from a smaller number of ribs, the number of the bent edges and root strips is also reduced. A few large ribs cost less than many small ones. The internal bracing of monoplanes is likewise cheaper. One-sided plywood covering as a substitute for internal bracing is usually preferable, being cheaper and producing less drag. Present-day methods of cantilever wing construction can be materially improved by using a single spar. Many constructional difficulties have been overcome by the use of wing sections with a fixed C.G. and slightly concave lower surface. One strong spar is considerably cheaper and lighter than two weaker spars of the same length. The cost of connecting single-spar wings with the fuselage might be reduced by further improving the methods of construction. The same applies to the assembling of ribs and connecting members.

A cantilever monoplane is cheaper than a biplane of equal wing area. Both the cost of the wing and the cost of the fuselage are smaller. The lower wing of a biplane must also be secured to the fuselage. Eight fittings are always more expensive than four twice-as-strong fittings. Biplane struts and bracings must also be manufactured. Braced-biplane fuselages require special stiffenings to take the stresses of the lift wires. Their cost is thereby increased and reaches that of the bent bottom flanges of cantilever biplanes, usually required for mounting the lower wing.

These considerations apply to fabric-covered light-metal wings as well as to wooden wings. According to the type of construction and tool equipment, metal edges, wing rib formers, fittings, bracings, etc. are, on the whole, more expensive than wooden ones. Fabric-covered metal wings produced in large numbers by stamping and pressing are cheaper than wooden wings. The difference between the cost of cantilever monoplanes and braced biplanes again becomes apparent when equal numbers are built with the same tool equipment. Sheet-metal covering is always more expensive and heavier than fabric covering. All-metal biplanes are almost unknown. They would be exceptionally expensive. The difference between the cost of fabric-covered metal and wooden wings may be expressed as follows. Considering the waste, duralumin in wing construction is 50 to 100% more expensive than wood with steel fittings. The cost of steel parts is no greater than that of wood with steel fittings. Very good tool equipments are necessary to keep the cost of labor for metal wings at the same level as that for wooden wings. General expenses are naturally increased by such installations. Any reduction in the cost of production necessitates an increase in the cost of the tool equipment.

Metal is cheaper than wood, when 200 to 400 airplanes of simple construction are built with a particularly well-designed tool equipment. Notwithstanding the low price of the raw material, the final cost of high-grade steel equals that of duralumin on account of greater machining expense. Mass production may also greatly reduce the cost of wooden wings. In series of twenty, the fabric covering amounts to about 20% of the cost of wooden wings and at least as large a portion of the cost of metal wings.

The above considerations account for the popularity of high-wing monoplanes with tapered cantilever wings or with braced rectangular wings for commercial purposes, especially of the small American types. The Klemm-Daimler is a typical German airplane, which is now selling well. The British Simmonds "Spartan" biplane represents a very interesting attempt to reduce the cost

(Fig. 7). This is a rival of the De Havilland "Moth." The upper and lower wings of the "Spartan" are alike. The lift wires and landing wires are of the same length and therefore interchangeable. The four ailerons are alike. The strut fittings are more expensive. The cost of this type is to be further reduced by stamping numerous identical parts. The reduction will be actually achieved, if the type sells as well as the De Havilland "Moth."

According to the above considerations, however, no price reduction can be effected comparable with that for high-wing monoplanes with continuous cantilever wings built in the same numbers. In addition to these reasons, there is another fundamental one that monoplanes have higher wing loadings and hence smaller wing areas. This is due to the ordinarily greater lift coefficient of monoplanes.

Biplanes exhibit many variations. Their historical development is a gradual transition from old and sometimes very expensive types to cheaper structural types. Three typical airplanes are compared in Figures 8-10. The stresses and lengths are given for flight case A, a weight of 1000 kg (2205 lb.) and a span of 10 m (32.8 ft.) being assumed for the calculation. A comparison can be made on this basis.

Single-field bracing is always cheaper than two-field bracing. When wing sections with fixed C.G. are used, the sum of the forces in the front and rear fields of the two-field bracing is equivalent to that of the single-field bracing, not only in case A, but in all cases. The stresses in the rear field of wing sections with traveling C.P. are greater in case B. Although one strong part is always cheaper than two half-as-strong parts, the latter added together are stronger than the single part in the case of a traveling C.P. Concentration of the single-field bracing in a single field with two spars enables a simplification of the fittings, provided the wings are staggered, so that the rear spar of the upper wing is over the front spar of the lower wing. This stagger also has aerodynamic advantages. Forward or backward spreading of the braces for the purpose of reducing the forces in the plane of the wing yields no appreciable result. Plywood covering is often substituted for internal bracing, the former usually requiring a large cross section. Then the case spreading produces an additional force in the lower fuselage longeron. The cost and weight of the wing attachments are increased by the absence of right angles, the forces in the fittings and in the lift wire being usually a little greater.

A continuous upper wing is cheaper than a two-part wing, the latter being in its turn cheaper than a three-part wing. The cost is further increased by pin joints (Gerber hinges) for three-part upper wings. The Udet Flamingo (Fig. 8) has such a pin joint. Its stresses and bending moments are much smaller than those of the Caspar "C 32" (Fig. 9). The wing weight of the

Flamingo is a little smaller than that of the "C 32," the ultimate load being nearly the same (wing loading minus wing weight multiplied by ultimate load factor). A further reduction in cost and in weight might have been effected by eliminating the sweepback of both wings, by increasing the dihedral angle of the lower wing and completely eliminating that of the upper wing and by making the latter continuous. Data subsequently collected by the author show that the flight characteristics are not impaired. Installing a cabane on the central section reduces the requisite number of fittings and increases the stresses and bending moments. In the case of a continuous upper wing, however, the remaining fittings then have to transmit in addition to the normal forces, only the tangential forces arising from the aileron moment about the vertical axis and are therefore very light and inexpensive. An airplane with a cabane may weigh no more than one with a central section, provided the installation of the cabane is facilitated by the fuselage, and the wing is thick enough to afford room for sufficiently strong spars. The cost may be further reduced by single-field bracing.

Experience with monoplanes shows that root bending moments are slightly reduced and drag moments greatly increased by tapering the wings. In the case of biplanes this would mean smaller stresses in the bracing and spars, with the spar sections increasing toward the wing root. At the same time the strut is shifted slightly inward; the bracing angles are better; the length of the bent portion of the upper wing and of the bracing wires is less; and the forces on the outboard strut are smaller (Caspar "C 35," Fig. 10). The fuel is carried in the upper wing. This wing has a specific weight of 7.5 kg/m² (1.53 lb./sq.ft.) and is one of the lightest types of this size. It must, however, be made of wood, since metal ribs and spars would be too expensive. In a twin-strut single-engine biplane the stresses and bending moments are never so much that it can be made lighter than a single-strut biplane, unless an exceptionally thin section is used. By doubling the number of joints and external bracings, the advantage of small stresses is outweighed, and the cost of the wing is considerably increased. The drag is also increased.

b) Control surfaces.- The above considerations can be extended to the control surfaces. The horizontal empennage of large airplanes is often as large as the wing of a small airplane, but differs in one important point. The number of ribs which can be made alike is very small. Fruitless attempts to use like ribs in the horizontal and vertical tail surfaces have often been made. Hence preference is given structural elements which yield the greatest variety of forms with the fewest tools. Thin-walled, weldable steel tubes are particularly suitable for this purpose. Cheap soldered steel sections for ribs, capable of being used for wings, cannot be used for control surfaces. The question of monoplane or biplane controls is subject to the same considerations as that of monoplane and biplane wings. A one-piece stabilizer, like a continuous wing, is cheaper than a divided one. It is very difficult to prevent unbraced stabilizers from vibrating. The fins are usually braced. A stabilizer-adjustment device requires many good joints to prevent vibration. It is often endeavored to replace adjustable stabilizers on large airplanes by adjustable auxiliary controls or spring balancers. The cost is also reduced by the consequent lightening.

Rudders are usually made of steel tubing with fabric covering, duralumin with fabric covering, or all-duralumin. The edge greatly affects the cost and weight. Rudders with axis shifted backward have a shorter bent edge than those with auxiliary balancing surfaces. The former are lighter and cheaper on account of smaller torque and simpler form. Fabric-covered steel-tubing rudders are always cheaper than the two other types. This is due to the fact that even very small steel tubes are no more expensive than duralumin. Tubes of different sizes are on the market and can be selected according to the stress conditions. The tool equipment is also cheap. The buckling and gripping strength is greater than that of open sections, while the surface to be coated is smaller. Welded connections are light and cheap. Round tubes do not chafe seams, as open metal sections easily do. Only a few sizes of duralumin tubes of small diameter are available. Their torsional stiffness is much smaller than that of steel tubes, owing to their small modulus of elasticity. The end connections are expensive and heavy. Fabric-covered rudders made of duralumin sections and sheet are rather heavy, usually heavier than all-duralumin rudders, since the buckling and gripping strength of open sections is small and their coated surface large. Riveted joints require ample flanges with edges and more weight. All-duralumin rudders are hollow. Their closing requires much work and considerable weight. However, being hollow, they have great torsional and bending stiffness, even with thin walls, and are therefore lighter than fabric-covered duralumin rudders. Besides, the large cross sections required by the latter have unfavorable shapes and cannot form the covering.

c) Fuselage.- We shall consider four fuselage types, namely, plywood, welded and riveted fabric-covered steel-tubing, and all-duralumin fuselages. The four types are compared on the basis of the cost per unit area, the airplanes being approximately of the same size. The cost increases with increasing size.

Two essentially different methods are used in plywood fuselage construction. According to the one, adopted in Germany to the exclusion of all others, a certain number of frames are first assembled on a slip, then the longerons are fitted in and the whole structure is covered. The other method, chiefly used in England (De Havilland "Moth"), begins with the construction of two sides, each framed by a top and bottom longeron. The sides are then connected by the bottom and top and the fuselage is completed by transverse frames, seats, etc. This method is cheaper when properly adapted to the design. The cheapest fuselage of sport airplanes is a simple type built along these lines.

Struts are now generally used in fabric-covered steel-tubing fuselages without wire bracing. This method is slightly cheaper, but its chief advantage is increased stiffness. The usually flat top is assembled in the inverted position, the lateral structures are set up and assembled by means of the bottom flange and members. After assembling internal struts and fittings, the whole structure is welded together. The quality of the welding depends on the quickness of the process. Piece work is therefore extensively employed. The welding of a seam, however, is a slow process. A saving of labor by using mechanical welding equipment requires much too expensive installations, owing to the great variety and complexity of the welded joints. According to another method the ends of the tubes are pressed into square sections and butt-riveted.* The cost of this method is greatly reduced by doing the work on mass production lines. Both types of construction are fabric-covered. Such fuselage types are now also built of drawn square section steel and duralumin tubing. The latter costs eleven to twelve times more and is 50% lighter. Butt-riveting makes no material difference.

Shell-type fuselages are built on frames. Open sections are cheaper than closed A sections and easier to assemble. They can be better protected against corrosion, which is partic-

*See Figure 19b, page 455, of the 1929 Zeitschrift für Flugtechnik und Motorluftschiffahrt.

ularly important in hulls and floats. The riveting of the covering is more than half the labor. The relation between the prices of shell-type and steel-tubing fuselages is affected by two factors, the first of which is production. As shown above, the welding time cannot be reduced. Besides, the cutting of tubes to the correct shape required for each individual connection cannot be materially expedited by mechanical means. This differs from sheet riveting methods, the cost of which can be reduced below that of a fabric-covered welded steel-tubing fuselage by means of an adequate tool equipment, provided a sufficient number of units - between 100 and 200 - is produced. The smaller figure is for cabin and military fuselages with many compartments. The installation of bulkheads, windows, doors, traps, floors, wall covering, upholstery, luggage nets, plates, instruments, etc., and the fitting of fairings, pipes, pulleys, tanks, pilots' seats, controls, switchboards, etc., is easier and cheaper in well-designed duralumin fuselages than in steel-tubing fuselages with strips, brackets, etc. Hence, steel-tubing fuselages will long be cheaper for large freight carriers with few installations. The smooth surfaces of the square tube ends and straps of riveted steel-tubing fuselages greatly facilitate assembling. This fuselage type is particularly cheap when a sufficiently large number is produced at a time. With good fittings and general equipment, combined with properly equipped workshops, this type of construction will remain superior to all others.

Hulls and floats are made of duralumin or wood. Wood absorbs much water which separates its plywood layers, thus continually requiring minor repairs. The corrosion of light metals necessitates frequent inspection. Bent, widely spaced frames greatly increase the cost. A few strong frames are much cheaper and lighter than several light frames. They enable the use of strong coverings which can be more easily handled than very thin coverings. Little attention is given the cost of construction of seaplane bodies, due to the difficulty of combining good take-off and alighting characteristics, the former requiring small water resistance and spray production and the latter adequate resistance to strong alighting impacts. Quadrangular or pentagonal sections with straight walls and slightly curved decks give the best results. Water-tight riveted seams with short rivet spacing are quite expensive.

Experience shows that the assembly of wing and fuselage, in which the latter is designed to fit into the top or bottom of a rigid wing, is very expensive. On certain high-wing monoplanes the wing fits into the top of the fuselage. This method increases the weight and cost without affording any advantage. Braced and cantilever biplanes are likewise affected by these considerations. The cut-out fuselage portion designed for a cantilever lower biplane wing is always expensive, and offsets the cost of bracing to a certain extent. The cost of the controls depends more than the cost of any other part on their design. The control parts in the pilot's cockpit are most economically made of silumin or elektron castings in sufficiently large numbers. The cost of the control transmission depends on the number of changes in direction. Cables and turnbuckles are much cheaper than rods, when straight transmissions are run from the control stick or column, foot lever or pedal, with only one external pulley for each aileron. The cost of steel rods and wires is approximately the same, when the number of pulleys with brackets and stiffenings affects the strength of the transmission and increases its friction beyond admissible limits. Duralumin rods are always more expensive but lighter than steel rods, since all means of reducing the cost of the former also apply to the latter.

The cost of the cabin depends on the number of seats. Modern leather chairs with elektron frames cost as much as expensive easy chairs. Framed triplex windows with windlass raisers are also expensive. As a rule there is a window for each seat. Most of the furnishings are bought on the market and included in the material account. The cost price of the standard-cabin equipment now used by the Deutsche Luft Hansa, is approximately 550 marks per seat. A like amount is required for labor and other expenses.

d) Power plant.- A steel-tubing engine bearer in front of the fireproof bulkhead or fire wall, is lighter than a duralumin bearer of equal strength, owing to the elaborate riveting necessitated by the oblique members of duralumin joints. The cost of a welded steel-tubing engine bearer is also greatly reduced by the low cost of the material and by the absence of complicated straps and connections.

The cost of engine installation is chiefly determined by the engine cowling which, with the fire wall, requires a large amount of sheet metal. In mixed construction, with the engine bearer and fire wall, it amounts to about 10% of the total cost of the airplane. The cost of the cowling is greatly reduced by a nose radiator since, without the latter, a cowling with good aerodynamic characteristics requires considerable stamping. As a rule, nose radiators not only reduce the weight and cost of the cowling, but simplify the water piping and reduce its cost. The weight and cost are further reduced by combining the auxiliary water tank with the upper tank of the nose radiator. Nose radiators are not the best aerodynamically, but no other arrangement offers sufficient advantages to justify its substitution for nose radiators, which are now gaining ground through evaporative cooling. The cost and weight of water-cooled engine cowlings is proportional to their area, which is slightly reduced by nose radiators.

Engine-control rods are more expensive than is usually thought. Welded steel tubular rods are cheapest, but light-metal rods are always lighter. Aluminum is good, owing to its great local and buckling strength. It is a little more expensive, but lighter. For a great buckling length it has the same modulus of elasticity and strength as duralumin. This property is greatly affected by structural details and space considerations. A small space usually requires several intermediate transmission levers, the installation of which is often difficult. A certain amount of free space between the engine and the fire wall greatly reduces the length of the rods. Throttle and ignition-lever handles will soon be put on the market as standardized parts. The "Ahrends control," which replaces the bell crank, is the first step in this direction.

The fuel piping often depends on the space between the fire wall and the engine. A small space greatly increases the cost of assembling. The essential parts of a large gravity tank installation include the piping from tank to strainer and from there to the stopcock, which may also form the connection through the fire wall and thence to the carburetor. Fuel pumps require additional pipes to the strainer running through the fire wall and returning through it to the stopcock. The list includes a control manometer with piping and installation. Two pumps are generally used for reasons of safety, and the length of the piping is increased accordingly. The fuel pump proper is an expensive mechanism, the operation and general equipment of which, including control instruments, causes further expense. Moreover, gravity tanks are safer, this being a remarkable instance in which safety does not increase the cost. A subdivision of the gravity tank for reasons of safety requires two pipes, one additional three-way valve and two fuel gauges. Two tanks cost more than one and safety again increases the cost.

The shape of the tank is very important. A smaller surface area for a given capacity reduces the consumption of sheet metal and the length of soldered, welded, or riveted seams. Wing tanks usually have large surfaces and are therefore heavy and expensive. Tanks of any material mounted on rests or fittings, instead of being supported by straps or saddles, are unpopular. They are also expensive, owing to the difficulty of transmitting forces through fuel-tight connections. Figure 11 shows two examples.

Brass is now used less extensively. Its strength is about 25 kg/mm² (35,559 lb./sq.ft.). Welded seams are comparatively heavy. In relation to their bending radii, welded elektron and aluminum tanks have thicker walls and therefore require a smaller number of partitions. The shape of aluminum and elektron tanks differs from that of brass or duralumin tanks. The latter are very light, welded and fuel-tight. Very narrow welded seams are expensive when produced in small quantities. Owing to the small quantity of German production, welded elektron tanks seem most suitable at the present time, considering their cost and weight. Approximately 7% of the cost of labor for airplanes with tubular steel fuselages and wooden wings is absorbed by the fuel and oil systems.

Wood propellers with fittings cost about one-third as much as metal propellers. Four-bladed propellers are more expensive than two-bladed ones. Three-bladed wood propellers are cheaper than two- or four-bladed ones, because shorter boards can be used for their construction. The hub stresses, however, require large cross sections and considerable weight. The machining of the blade connections with the hub, especially for three-bladed and one-piece four-bladed propellers is very expensive. The cost of different propeller types of equal diameter compares as follows: two-bladed, 100%; divided four-bladed, 200%; one-piece four-bladed, 240%; and three-bladed 220%, without hub.

e) Landing gear.- The wheels absorb half the cost of a landing gear. V-type or bow landing gears are being gradually replaced by those with shock-absorbing struts. Elektron and silumin castings are now extensively used for struts with rubber shock absorbers. Tires take 70% of the cost of a wheel and this figure cannot be reduced by increased production. The rubber cables of good shock-absorbing struts likewise take a great part of their cost of construction. Inasmuch as the price of rubber is not reduced by increased consumption, oleopneumatic struts are coming into use. They are built on mass-production lines by subsidiary factories and their cost will be gradually reduced to a considerable extent. Besides, they are lighter than struts with rubber shock absorbers. Data on their durability and tightness after a long period of operation are not yet available. Chrome-nickel-steel axles are more expensive than carbon-steel axles, but must be frequently used for large wheels.

Effect of Size

<u>a) Wings and control surfaces</u>.- On extending the previous considerations regarding cantilever biplanes to a biplane with independent cantilever wings, several examples of which have already been built, the following conclusions are reached. If the joint area of the two wings is replaced by a single cantilever wing, two spars only are required which, although of larger size, are nevertheless cheaper. Besides, a smaller number of ribs and only two bent edges, two ailerons with controls, two pairs of wing-root fittings are required, instead of twice this number of parts for biplanes. Hence, a monoplane wing would be cheaper. In other words, large surfaces are cheaper per unit area than small surfaces. This is extremely important for light airplanes. For a uniform spacing of the ribs, the price of a wing per unit area is inversely proportional to its area. Biplanes of less than 50 hp are so expensive they cannot compete with monoplanes of the same power. Their upper or lower wing is very small. The wing loading, usually increasing with the size of the airplane, requires a narrower rib spacing and hence a greater number of ribs. This, however, is not very important, since the cost of the different parts, referred to the unit area, is greatly reduced with increasing size.

Enlarging fabric-covered wings reduces their price per unit area, until a point is reached where they have to be divided. Experience shows that the best size for dividing wings parallel to the spars is usually reached when rail transportation becomes impossible. Owing to the cumbersome length of the ribs, the transportation, covering, coating and storing of the whole wing becomes difficult. No definite figures can be given in this connection, since they are always slightly affected by the tool equipment and by details of construction. Under these conditions very large biplanes are more economical than monoplanes.

Division of the wing parallel to the spars is very expensive. Individual parts or fields of the wing are not interchangeable, due to the extreme lightness of the front and rear portions which lack sufficient stiffness when separated from the spar. They always warp slightly after removal from the jig and must therefore be firmly secured to the spar. This is very expensive for wings divided along four lines parallel to the spars and extending over the whole span. Each box has attachment fittings and stiffenings which provide a certain rigidity when the boxes are dismantled. The strength of the edges to which the covering is attached must be proportional to the tension of the fabric. In the case of undivided wings this consideration applies to the leading and trailing edges only, while in the present case it extends to the division edges.

Metal-covered wings differ slightly from fabric-covered ones. Metal covering takes a much greater part of the cost of production than fabric covering. The cost per unit area of spars, ribs, bent edges, ailerons and hinges, attachment fittings, etc., decreases with increasing size, while that of the covering remains unchanged. Inasmuch as the latter takes a great part of the cost of the finished wing, the final cost reduction per unit area is small. The cost of the expensive metal covering is further increased by the numerous joints necessitated by the separation of the wing into several boxes. Each line of separation has two riveted seams instead of one in the undivided wing. Besides, the spacing of the rivets must be reduced. The difficulty of assembling leading and trailing edges 12 to 14 m (39.37 to 45.93 ft.) long, justifies the additional cost of a further subdivision into boxes of approximately 2 m (6.56 ft.) length to reduce the cost of assembling.

Wooden wings are seldom larger than 100 to 200 m² (1076.4 to 2153 sq.ft.). For static reasons the weight per unit area (wing weight) increases with the size of the wing. Metal takes a greater part of the cost of a wing than wood. Hence, the cost per unit area of large metal wings does not increase, with increasing size, in the same proportion as that of wooden wings.

The construction of airplanes exceeding 20 to 25 tons (44,000 to 55,115 lb.) is not only a static problem involving the weight of the airplane parts, but also one of production. Large airplanes are heavier and more expensive, since the division of parts increases their weight and cost. Other factors must be added, such as stiffenings and attachment fittings of engine nacelles, landing gears, wing-tip floats, handling-truck connections, passages in the wings, etc. Seaplanes must have water-tight compartments and doors, water-tight external riveting and inspection holes, lifting rings for transportation purposes, etc. For these reasons airplanes of more than 12 tons weight are very expensive.

b) Fuselage.- Any further increase in the size of plywood fuselages is out of the question. This does not apply to steel-tubing and shell-type fuselages. The surface of a fuselage undergoing a conformal increase grows as the second power and its volume as the third power of its linear dimensions. There is no definite law for stresses and bending moments. Landing impacts and stresses in the control surfaces are absorbed by different parts of the airplane structure, which must be dimensioned accordingly. The relative importance of the two groups of forces depends on the load distribution in the fuselage. The requisite load factors decrease with increasing size of airplane. The flange and web thickness of modern training and mail planes with steel-tubing fuselages is about the same as for large commercial airplanes. The change in the diameter of the tubing is nearly proportional to the size of the fuselage. Hence, the weight of small and large steel-tubing fuselages per unit area is usually 4.0 to 5.5 kg/m² (.82 to 1.13 lb./sq.ft.). Another very important point is that the number of joints of the fuselage structure is practically unaffected by increasing its size. Some very large fuselages have a smaller number of joints than those of sport airplanes five to seven times lighter. Hence, the number of tubes and riveted or welded joints is practically constant for all fuselage sizes. For the same thickness of metal, the length of the welded seams or the size of the riveted sections is roughly proportional to the length of the fuselage. On the other hand, labor and material vary as the square root of the area. The cost of the fabric covering is proportional to the area. The same applies to floors, linings, etc. The percentile cost of wing, landing gear and tail-surface fittings is rather high and does not follow any definite law. Fittings cut from the solid are usually more expensive than sheet-metal fittings. The fittings for very large fuselages, the steel-tubing structure of which is cheaper on account of its size, take 50 to 55% of the cost of the covered structure, not including controls and equipment, while, in small fuselages, these figures are only 20 to 30%. The cost of the covering of very large fuselages is between 15 and 20%. The rest is taken by the steel-tubing structure and fittings (Caspar "C 35" - Fig. 10).

With increasing size the cross sections of the upper and lower flanges of shell-type fuselages are governed by the same considerations as steel-tubing fuselages. The spacing of the frames must be kept within definite limits. Certain large airplanes are provided with main frames corresponding to the stringers of steel-tubing fuselages. The spacing of the intermediate auxiliary frames is independent of the size of the fuselage or hull and determined only by the requisite stiffness of the covering. The cost of labor for the construction and erection of these frames does not depend entirely on their size but also on the kind of sections, corner plates, etc. The cutting, tacking and riveting of the covering takes approximately 60% of the cost and varies directly as the area. The production and attachment of the fittings vary considerably, as in the case of steel-tubing fuselages. In short, the cost per unit area of shell-type and steel-tubing fuselages decreases with increasing size. This cost reduction is smaller in the first case, in which the part of the cost of the covering which is directly proportional to the area, is greater than in the second case.

c) Landing and float gears.- The spacing of the bottom timbers of wooden or duralumin floats depends on the estimated water pressure. The beam spacing of walkable decks is independent of their size. Similar considerations apply to the side walls, which take part of the water pressure. The size of a float may be greatly increased, without changing the number of bulkheads, hatches, and fittings. The cost can be reduced by special attention to details. Besides, the cost per unit area decreases with increasing size, since the closing of small hollow bodies is relatively more expensive than that of large ones. The influence of the float volume is decisive. It increases as the third power and the float area as the second power of the increase in size. This clearly demonstrates a decrease in the cost of production per unit volume, which is often accompanied by a decrease in the cost of production per unit area.

The variation in the cost of the many different float gears does not follow any definite law. For small variations, the conditions are probably similar to those of steel-tubing fuselages. In practice an increase in the total weight from three to six tons does not, as a rule, double the weight of the float gear. It is still more difficult to estimate the cost of the great number of different landing gears, but something can be said regarding the wheels. They are loaded in proportion to their projection, i.e., the diameter by the width. The cost, varying as this product, increases very rapidly, as much as fourfold for an increase of the wheel load from one to two tons, or twofold on the basis of the carrying capacity of the airplane. Above two tons the cost increases more slowly and decreases slightly again for very large dimensions.

<u>d) Power plant</u>.- Two single-engine airplanes - a large one with an 800 hp engine and a small one with an 80 hp engine - are compared below. They have the same power loading, their weights being in the ratio of 1 to 10. The area per horsepower of the engine cowling and fire wall is about the same for both. The cost per horsepower of the engine is not much affected by its size or type, being about the same for vertical and radial

engines. Due to the great cost of cooling installations, air-cooled engines would have the advantage except for certain expensive parts. The bearers of vertical and radial engines are governed by different considerations, but the size of both types varies as that of the fuselage. The number of joints is constant. The bearer of an engine is neither tenfold heavier nor tenfold more expensive than the bearer of an engine one-tenth as large. The small engine has a gas throttle and ignition lever, a circuit breaker, starting magneto, revolution counter and fire extinguisher. The large engine also requires oil thermometers and pressure gauges. Water-cooled engines require water thermometers, while fuel pumps require fuel-pressure gauges. Hence the large engine has a very small number of instruments per horsepower, but it also requires a starter. Both airplanes have the same speed and are equipped with water-cooled engines, their radiators being of the same type and having strictly identical piping. The ratio of the frontal area of the radiator to the power is therefore constant. Its periphery and hence the size of the water tank increases as the square root of the frontal area or of the engine power. The attachment of the large radiator does not cost ten times more than that of the small one. The size of the water pipes is governed by considerations similar to those mentioned above for fuselage structures and engine bearers. The analogy between two airplanes of different sizes is of course not perfect in practice. According to the above examples, the cost of engines per horsepower decreases with increasing size.

The size of a propeller undergoing a geometrically similar increase throughout its diameter, increases as the fifth root of the power output at a constant r.p.m. and as the fourth root of the peripheral velocity. At a constant angular velocity the centrifugal force necessitates such a strengthening of the hub section with increasing diameter, that the weight increases as the fourth power of the diameter. The cost increases as the 2.4 power of the diameter. Hence, the cost of the propeller varies either as the 2.4/5 power of the output at constant r.p.m. and peripheral velocity, and as the 2.4/4 power of the output at constant r.p.m. and peripheral velocity. This shows again a marked tendency toward a cost reduction per horsepower with increasing size.

Effect of Power-Plant Decentralization

Three or four engines are often used to increase the safety. The additional cost of decentralization on a standard commercial airplane of four to seven tons is calculated on the assumption that the single central engine has the same power as the entire decentralized power plant. In practice the latter must have a greater total power for obvious reasons.

As already shown, the difference between the cost per unit power of large and small engines is slight and follows no definite law. The same consideration applies to cowlings and fire walls. A large engine bearer, however, is much cheaper than three or four smaller ones. The installation of lateral engines with cowlings and fire walls requires additional bearers, struts, fittings, wing stiffenings and fairings. In substituting three engines for a single central engine, the size of the cowling and fire wall of the central engine is scarcely reduced. The number of controls and instruments is increased three or four times. Besides, one standard revolution counter is replaced by two and sometimes even by four distant-reading tachometers. Difficulties are increased by the use of long push rods and pipes. Three or four engines require more than one fuel or oil tank and radiator. The cost of all these parts increases with decreasing size. Several engines together cost more than a single engine of the same power, the cost increasing with the number of engines. The weight is naturally increased by additional tanks and pipes. The assumption previously made, that the engine power need not be increased for the same pay load, is therefore incorrect, and the power must be increased. Also the wing must be enlarged to carry more powerful engines, this constituting another reason for increasing the engine power. The greater drag of three or four engines necessitates a further increase of power, if the airplane is to maintain its speed. These considerations lead to larger engines with greater amounts of fuel and oil, larger tanks, etc., thus necessitating a further increase of power. The cost increases with the number of engines.

The weight reduction attempted on large airplanes, by locating certain loads in the wings, leads to conflicting results, since the loads increase every time they are divided, and the drag is also increased. The fact that only the weight of the wing spar is reduced by a load distribution over the span is often overlooked. The other conditions remain unchanged. The wing weighs approximately 15% of the whole airplane, one-half of this figure, or 7.5%, being absorbed by the spars and struts. A reduction to 5% is the maximum obtainable by an outward shifting of the loads. This reduction is always offset by increases in the individual loads.

C o n c l u s i o n s

The historical development is a gradual transition to cheaper types of construction. Two-strut and three-strut biplanes are replaced by the single-strut type. The braced "Taube" was transformed into a strongly braced or cantilever monoplane. The wood-and-wire fuselage has disappeared. Sufficient experience has not yet been gained in all-duralumin aircraft construction to permit competing effectively with mixed construction as regards cost. The latter is a step toward cheaper methods of construction, as evidenced by the fact that one of the oldest German metal aircraft factories is now making fabric-covered duralumin wings.

The two calculations for the determination of the best aerodynamic and static solutions are often replaced by a single calculation giving the most economical type of construction, especially for wings, tail surfaces and fittings, struts, bent edges, etc., for wing sections with fixed C.P. and in connection with decentralization.

The cost of airplanes, especially of single-engine types, decreases with increasing size. Their cost per unit area of wing, tail surface or fuselage is inversely proportional to the size. Engine accessories of very small airplanes are very expensive. Extra-light airplanes of very small size will eventually disappear. Such has been the fate of light motorcycles and bicycles with auxiliary motors, built six to eight years ago, and which have now completely disappeared. In an attempt to produce cheaper types, manufacturers neglected the convenience and safety of their patrons. This and the short life of their products made them gradually lose their market. Sport airplanes should therefore be kept above a certain minimum size limit, especially because any further reduction would bring no appreciable advantage. Airplanes carrying two persons must be fully reliable at cruising speed with throttled engine.

With a very few exceptions, safety increases the cost, as shown particularly by decentralization. Economic considerations lead to the conclusion that heavier engines, which are more reliable without being more expensive, are the best means of increasing safety. Large tanks and pipes are so light, as compared with their capacity, that they afford much better means of improving safety than small tanks. This consideration applies to other engine accessories of high-powered single-engine airplanes.

The above considerations determine the limit of decentralization. It not only impairs the flying characteristics and reduces the carrying capacity, but greatly increases the cost of production. On the other hand, decentralization reduces the number of emergency landings only when very powerful engines are used. Otherwise, the failure of an engine reduces the safety of multi-engine airplanes instead of increasing it. These and other considerations favor powerful engines, enabling a 50% reduction of the normal power at cruising speed with a corresponding gain in safety. The advantage of several engines is problematic, since their loading increases with the number, while the degree of reliability is correspondingly reduced. Moreover, multi-engine airplanes are slower, much larger and less maneuverable in emergency landings than single-engine airplanes of the same carrying capacity.

Middle-sized ships are now built with a single engine, while only very large steamers have several engines. According to the above considerations, large engines should be built and used on middle-sized single-engine airplanes or on very large three-or-four-engine types, instead of using a larger number of lighter engines.

Legends

Fig. 12. Dornier Komet III Merkur and Fokker F VII. The Merkur was formerly built in large numbers and did not cost much more than the Fokker F VII, the fabric-covered steel-tubing fuselage of the latter being larger and longer than that of the Merkur. The smaller metal-sheathed duralumin fuselage of the Merkur costs as much as that of the Fokker, though the latter carries two more passengers. The wooden Fokker wing is tapered and has differing ribs, while the strutted Merkur has like ribs and spars and uniform continuous flanges. A large portion of the wing is covered with metal. Fabric covering would probably bring its price nearer to that of wooden wings.

Fig. 13. Short Çalcutta and Dornier Superwal. Both types serve the same purpose. The Calcutta is a biplane with bent frames and duralumin ribs. With practically the same capacity and speed, the costs of the two flying boats, with engines, have a ratio of 8 to 5.

Fig. 14. Albatros Schlafwagen (sleeping car) and Caspar C 35. Both airplanes have same power, the single-engine type being 55 to 60 km/h (34.2 to 37.3 mi./hr.) faster with a much heavier load. The cost of the Schlafwagen stands in a ratio of 8 to 5 to that of the C 35, built by the writer, both airplanes being taken without engines. The C 35, however, was built several years after the Schlafwagen.

Fig. 15. Rohrbach Roland and B.F.W. M 20. Both types carry eight to ten passengers. The single-engine M 20 is about 15 km/h (9.32 mi./hr.) faster than the three-engine Roland. Their costs, without engines, are 2 to 1. The M 20 is designed on cheaper lines. Its wing, which is not fitted into the fuselage, and its tail surfaces are partially covered with fabric. Yet the greater cost of the Roland is chiefly due to decentralization of the power plant. The M 20 having an air-cooled engine and the Roland having water-cooled engines, the decentralization of the cooling system must also be considered.

Fig. 16. Fokker F VII and F VII 3 m. These two airplanes, built on similar lines, are excellent examples of the single and the multi-engine types.

Airplane engine	F VII 1 Jupiter	F VII 3 m 3 Titan
Engine power	500 hp	3 × 250 hp
Weight empty	2150 kg (4740 lb.)	2780 kg (6129 lb.)
Crew	160 " (353 ")	160 " (353 ")
Fuel	490 " (1080 ")	560 " (1234 ")
Pay load	800 " (1764 ")	1000 " (2205 ")
Total weight	3600 " (7937 ")	4500 " (9921 ")
Wing area	58.5 m² (629.7 sq.ft.)	67.6 m² (727.6 sq.ft.)
Span	19.3 m (63.3 ft.)	21.7 m (71.2 ft.)
Range	900 km (559 mi.)	700 km (435 mi.)
Maximum speed	197 km/h (122.4 mi./hr.)	185 km/h (115 mi./hr.)

The speed and range of the three-engine F VII 3 m are smaller than those of the single engine F VII, since it would otherwise require more powerful engines, more fuel and a larger wing. The costs, without engines are 1 to 1.3, and with engines 1 to 1,35.

Fig. 17. Udet Condor and Focke-Wulf Möwe. The four-engine Condor was designed by the writer under the regulations restricting airplane construction in Germany. Four 135 hp Salmson engines had been originally planned, but were finally discarded. With the Salmson engines the speed of the plane would have been 175 km/h (108.7 mi./hr.) instead of 162 km/h (100.7 mi./hr.) with four 100 hp Siemens engines. The Möwe has approximately the same speed with an ungeared 420 hp engine. A speed of 175 km/h is thus attained with 4 × 135 = 540 hp, for the Condor, and with 1 × 420 hp for the Möwe. The speed of the Möwe with geared Jupiter engine is 198 km/h (123 mi./hr.). Owing to the marked decentralization of the Condor, the relation between the costs of the two types is less favorable than in the case of the M 20 and the Roland, the difference between the fuselage structures and all other details being given due consideration. The Condor achieved no great success, owing to its small engine power. The great length of the propeller shafts did not affect their operation.

Fig. 18. Junkers G 24 and F 24. Several old three-engine types were transformed by substitution of a powerful central engine. This arrangement is an example of retrogressive development. The F 24 was equipped with the first heavy-oil engine.

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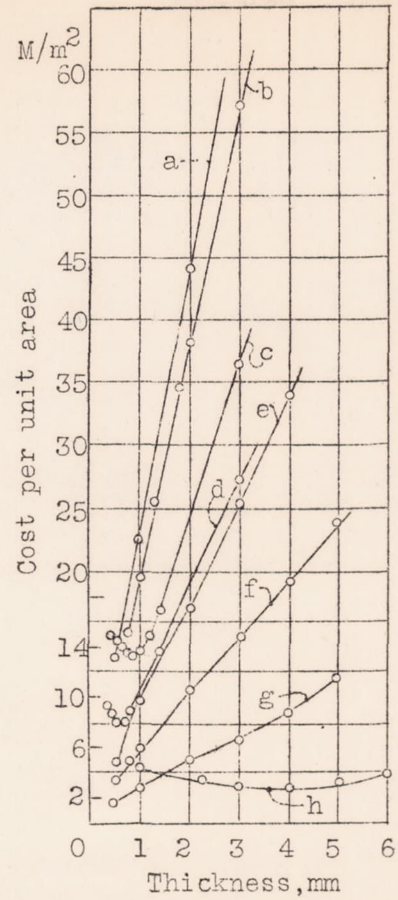
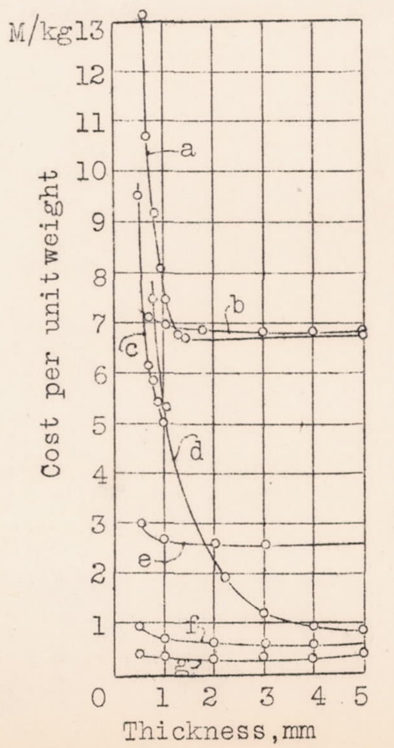


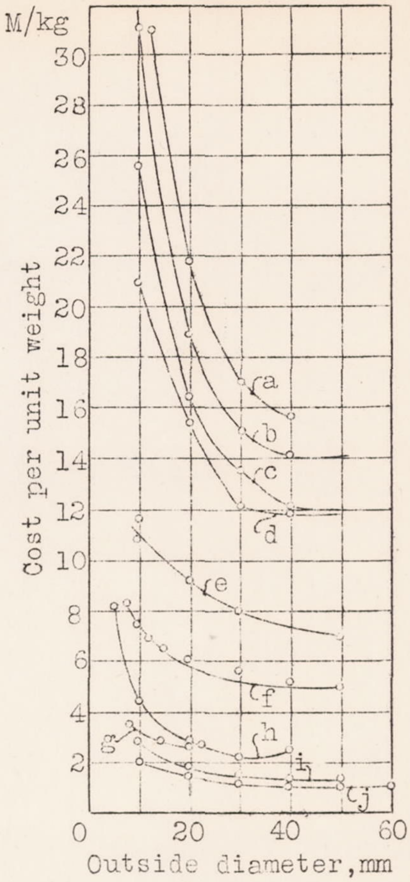
a, Medium-hard brass
b, Duralumin, Kz=38-42 kg/mm^2
c, Elektron Z3 and AM 503, kz = 20-24 kg/mm^2
d, Elektron AZM, kz=28-32 kg/mm^2
e, Aluminum
f, Sheet steel, kz=60-70 kg/mm^2
g, Sheet steel, kz=34-42 kg/mm^2
h, Plywood

Fig.1 Cost of materials per unit area.



a, Elektron Z3 and AM503
b, Duralumin
c, Elektron AZM
d, Plywood
e, Medium-hard brass
f, Sheet steel, kz=60-70 kg/mm^2
g, Sheet steel, kz=34-42 kg/mm^2

Fig.2 Cost of materials per unit weight.



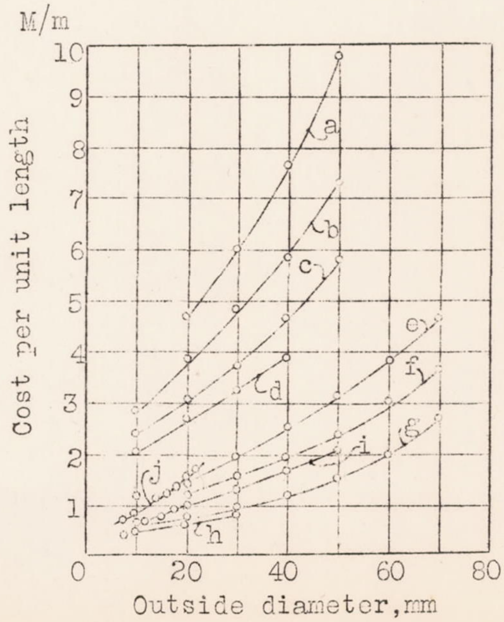
a=0.75
b=1.0
c=1.5
d=2.0
Duralumin tubes, kd=38 kg/mm²

e, Equivalent open duralumin sections, kd=30 kg/mm²

f=1.0, Aluminum tubes

g, Copper tubes
h=0.5
i=1.0
j=2.0
Steel tubes, kd=50 kg/mm²

Fig.3 Cost of tubes and section metal per unit weight.



a=2.0
b=1.5
c=1.0
d=0.75
Duralumin tubes

e=3.0
f=2.0
g=1.0
h=0.5
Steel tubes

i=1.0, Aluminum tubes
j, Copper tubes

Fig.3 Cost of tubes per unit length.

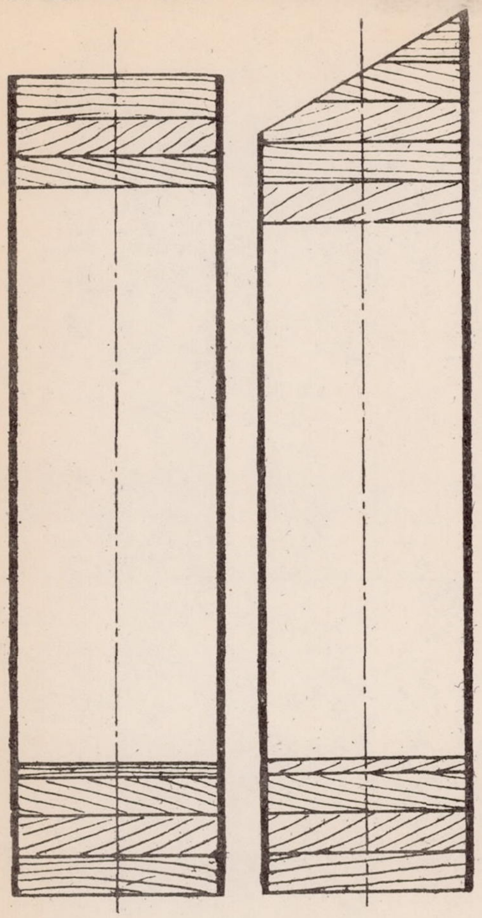


Fig.5 Sections of typical wood spars.

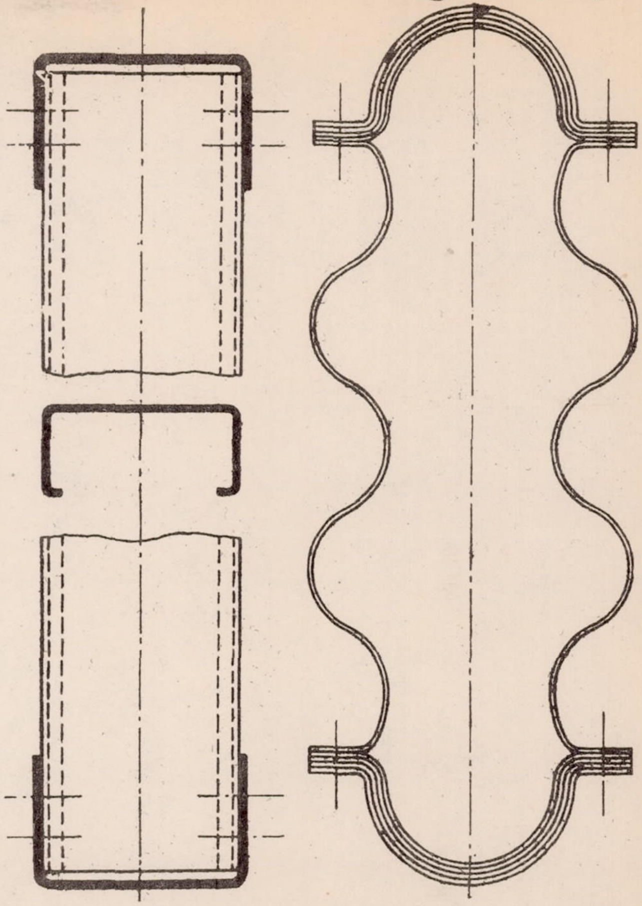


Fig.6 Sections of typical metal spars.

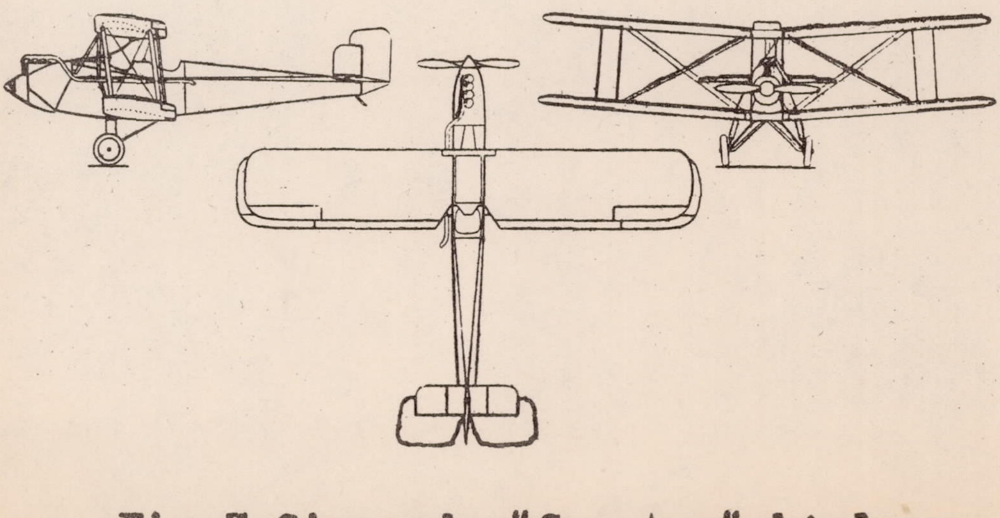
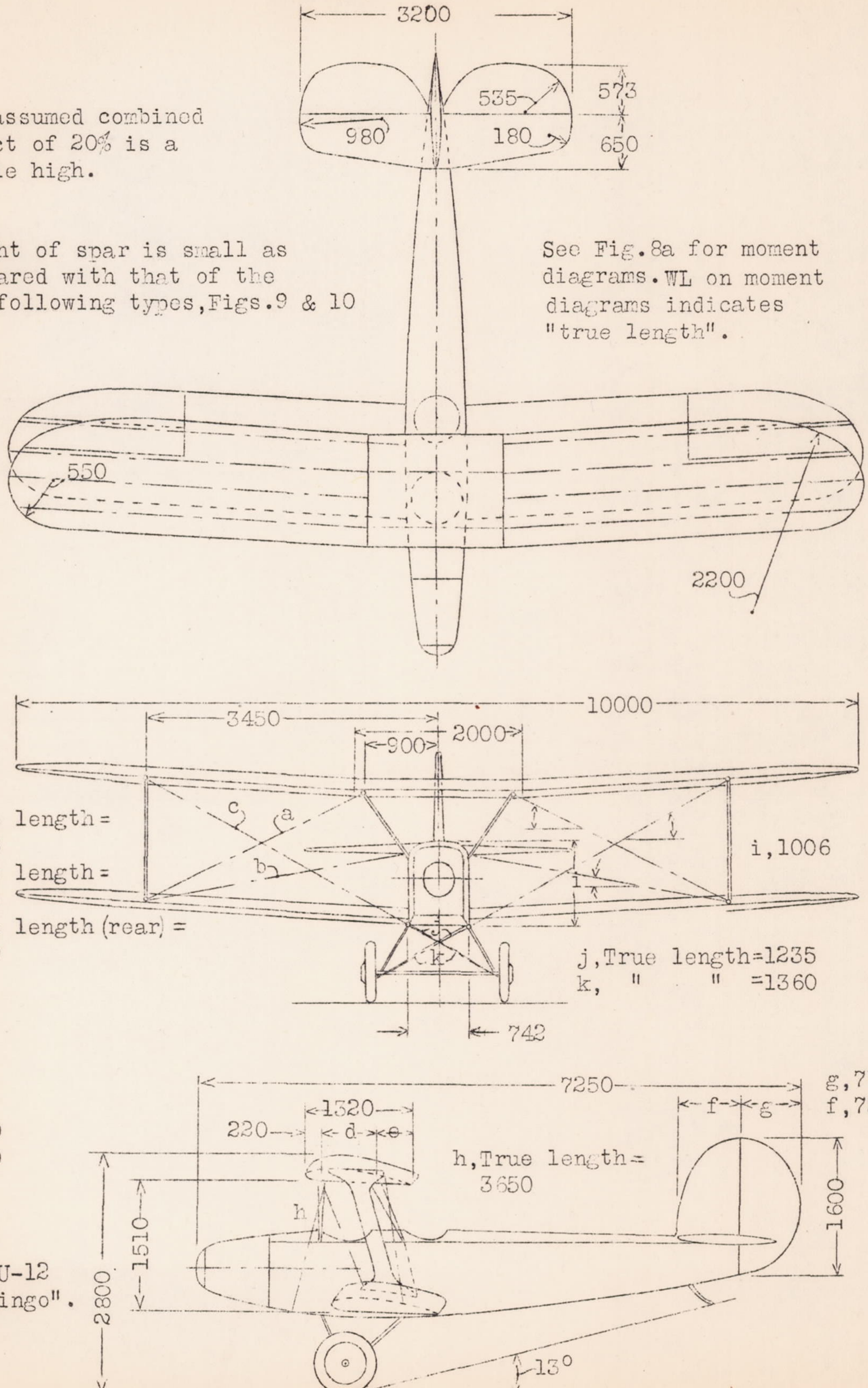


Fig.7 Simmonds "Spartan" biplane.

The assumed combined effect of 20% is a little high.

Height of spar is small as compared with that of the two following types, Figs.9 & 10

See Fig.8a for moment diagrams. WL on moment diagrams indicates "true length".



a, True length = 2875
b, True length = 3125
c, True length (rear) = 3490

i, 1006

j, True length = 1235
k, " " = 1360

g, 715
f, 750

d, 650
e, 450

h, True length = 3650

Fig.8
Udet U-12
"Flamingo".

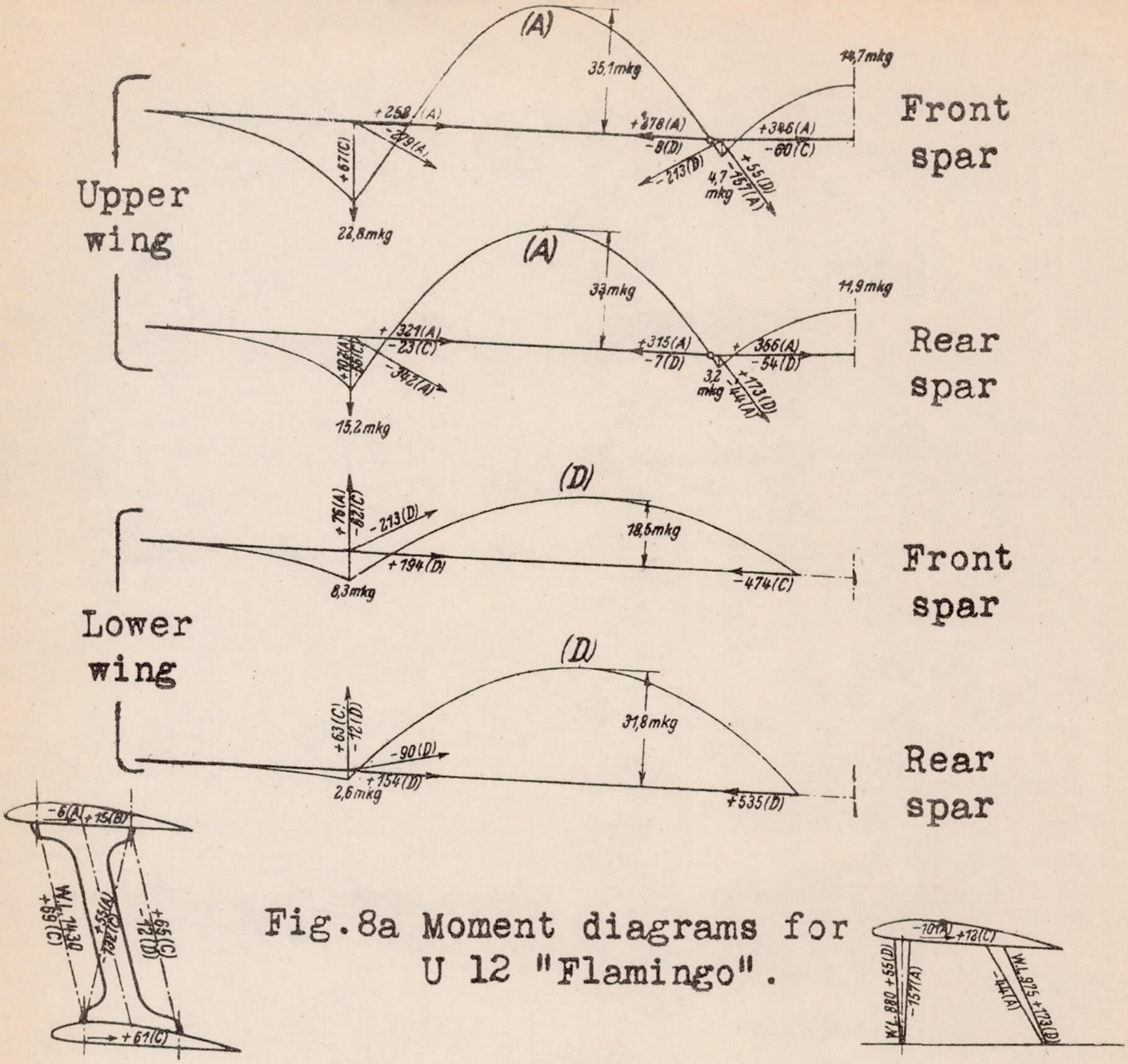


Fig.8a Moment diagrams for U 12 "Flamingo".

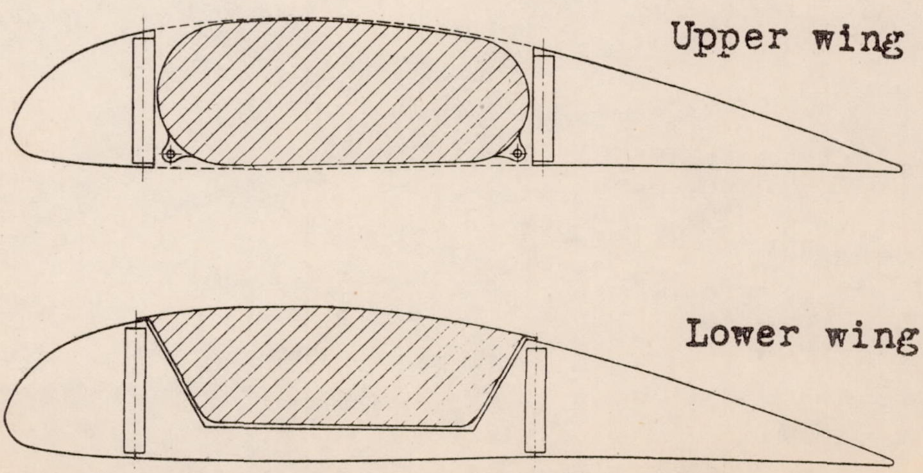
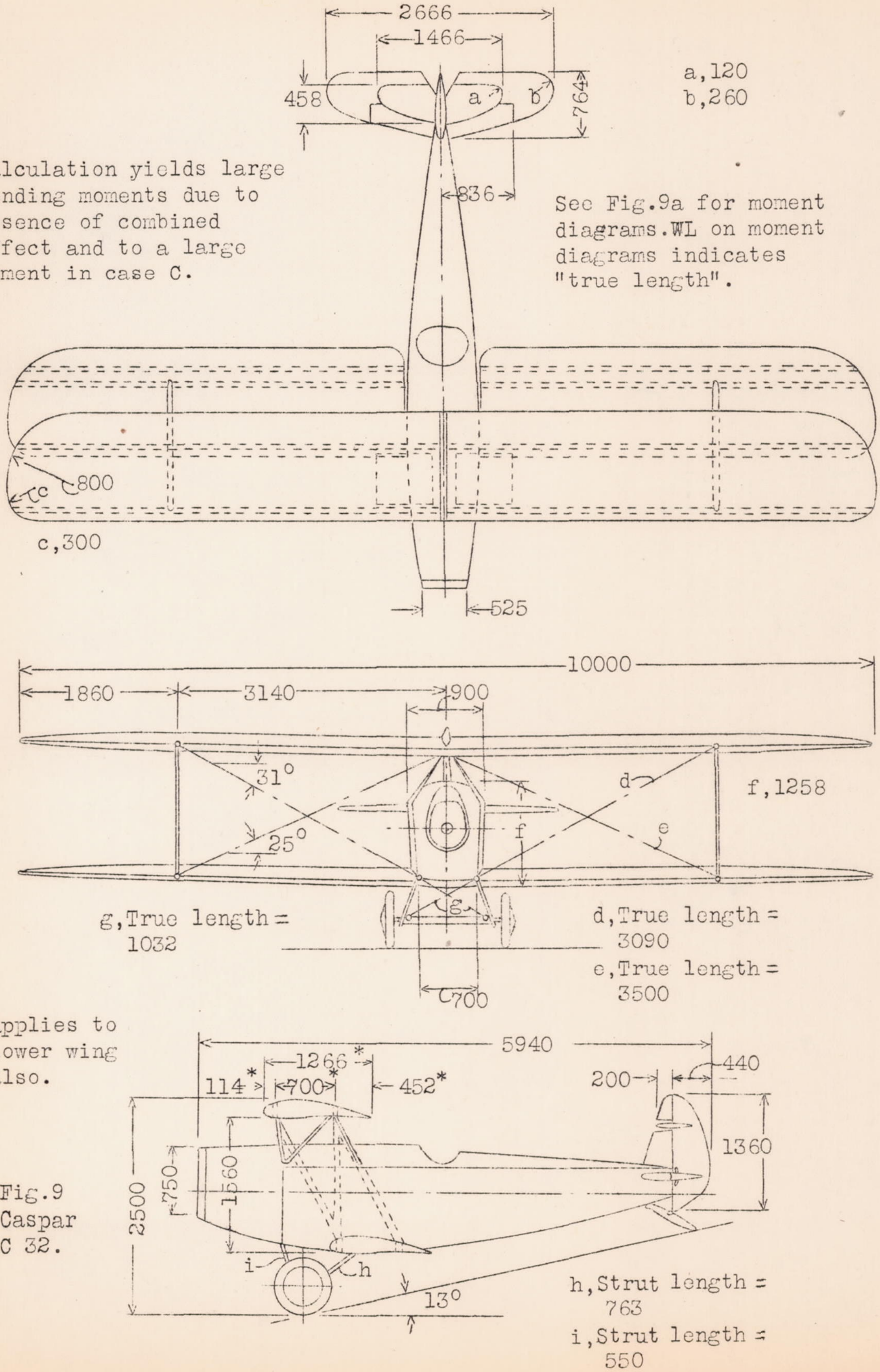


Fig.11 Wing tanks in "C 36"

Calculation yields large bending moments due to absence of combined effect and to a large moment in case C.

See Fig.9a for moment diagrams. WL on moment diagrams indicates "true length".



*Applies to lower wing also.

Fig.9 Caspar C 32.

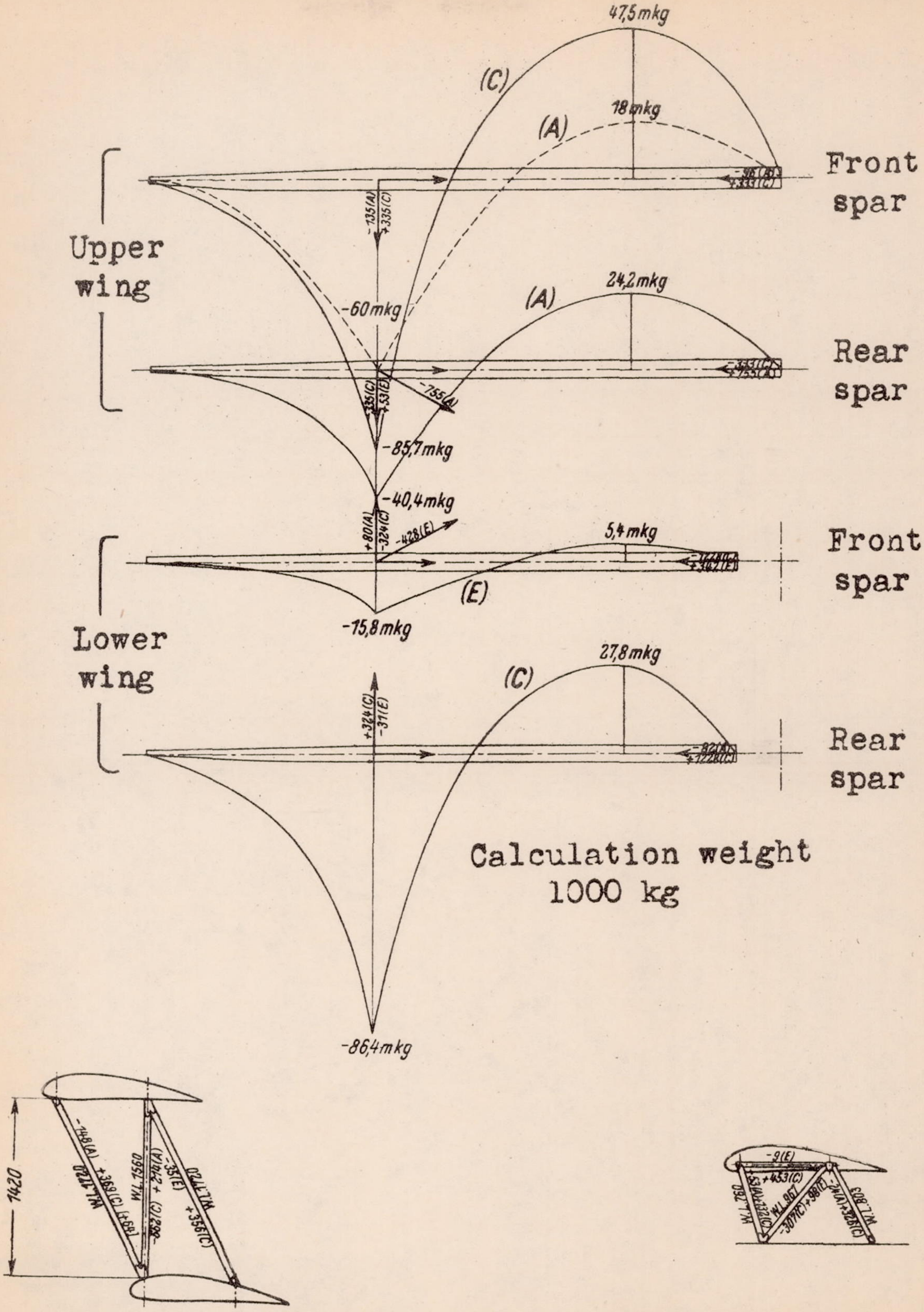
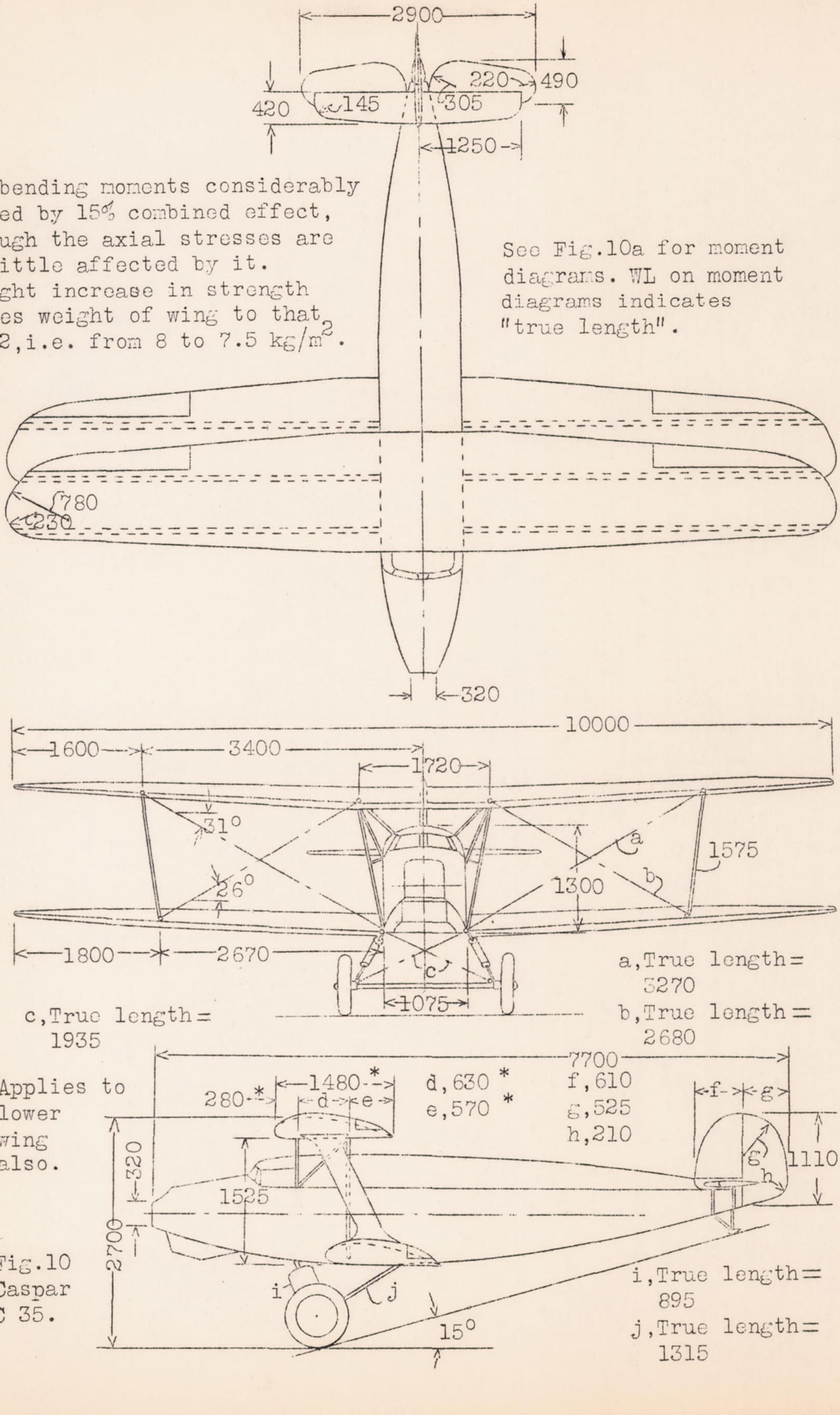


Fig.9a Moment diagrams for "Caspar" C 32.

Spar bending moments considerably reduced by 15% combined effect, although the axial stresses are but little affected by it.
A slight increase in strength reduces weight of wing to that of C32, i.e. from 8 to 7.5 kg/m².

See Fig.10a for moment diagrams. WL on moment diagrams indicates "true length".



*Applies to lower wing also.

Fig.10 Caspar C 35.

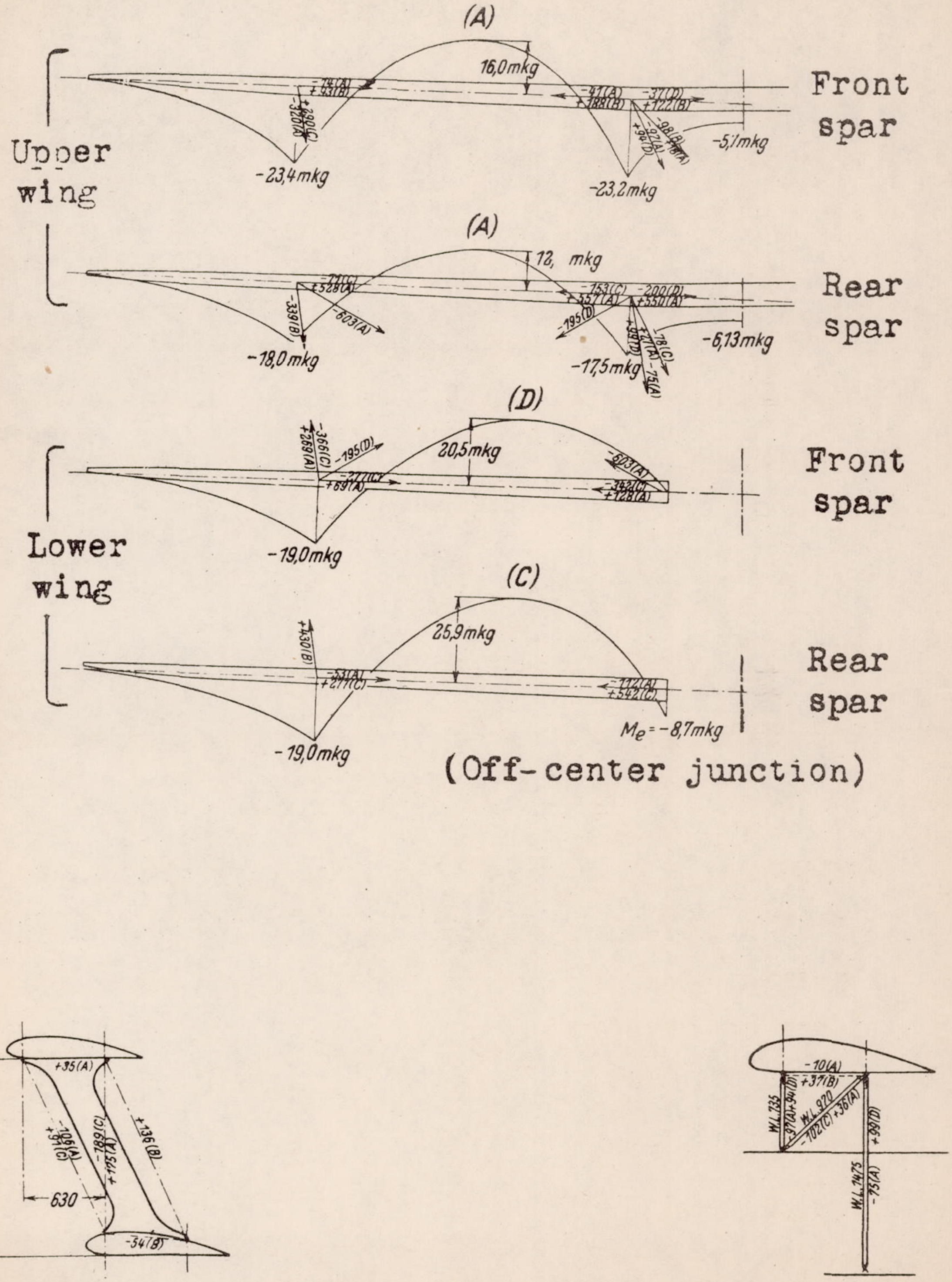


Fig.10a Moment diagrams for "Caspar" C 35.

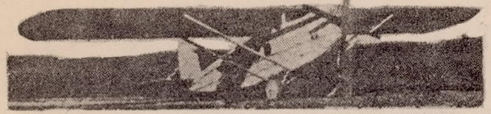
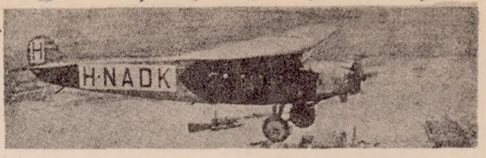



Fig. 12

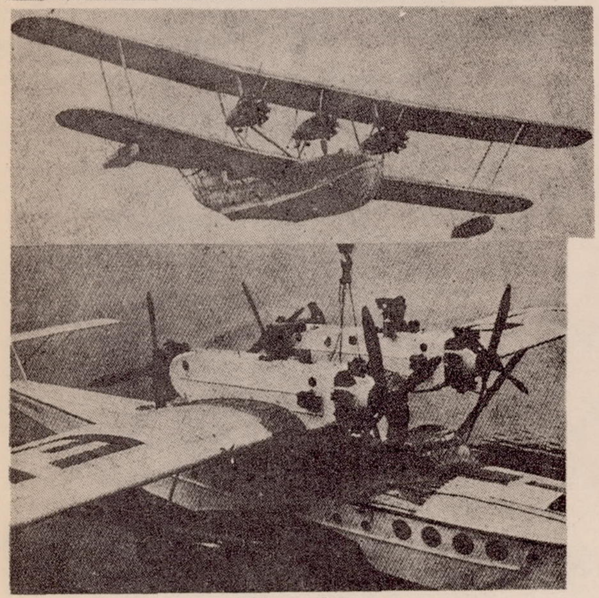


Fig. 13

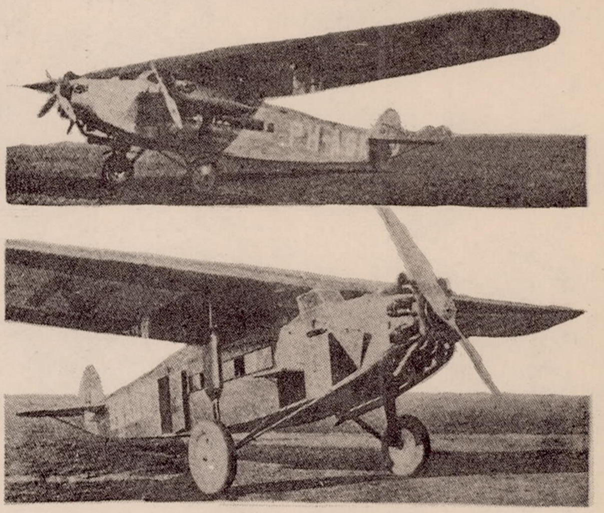


Fig. 16

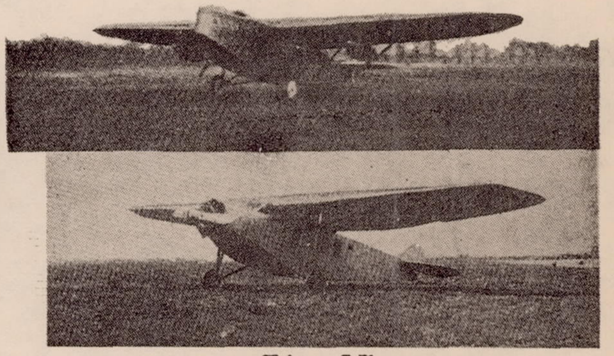


Fig. 17

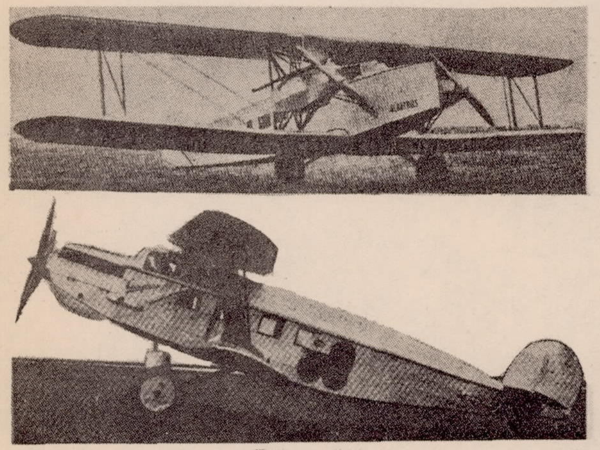


Fig. 14

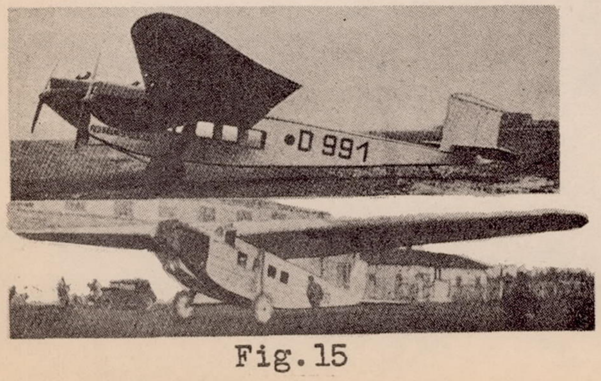


Fig. 15

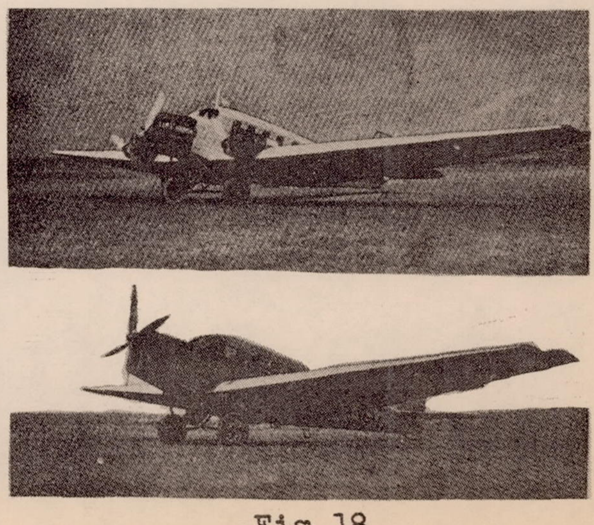


Fig. 18